

# Atomic Quantum Memory for Photonic Qubits via Scattering in Cavity QED

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We investigate a scheme of atomic quantum memory to store photonic qubits in cavity QED. This is motivated on the recent observation that the quantum-state swapping between a single-photon pulse and a  $\Lambda$ -type atom trapped in a cavity is ideally realized via scattering for some specific case in the strong coupling cavity regime [T. W. Chen, C. K. Law, and P. T. Leung, *Phys. Rev. A* **69**, 063810 (2004)]. We derive a simple formula for calculating the fidelity of this atom-photon swapping for quantum memory. We further propose a feasible method which implements conditionally the quantum memory operation with the fidelity of almost unity even if the atom-photon coupling is not so strong. This method can also be applied to store a photonic entanglement in spatially separated atomic quantum memories.

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Combined systems of atoms and photons have been studied extensively to construct quite promising and efficient quantum networks for information processing and communication [1]. In these quantum networks, quantum-state transfer between photons and atoms (matter) and storage of quantum states are particularly important. Then, numerous methods to implement the quantum-state transfer and quantum memory have been proposed and investigated in various manners [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12]. The cavity QED is among the promising schemes to realize such quantum-state operations, which utilizes strong interaction between single atoms and photons inside cavities [13]. Specifically, quantum-state transfer and manipulation are made between a single atom and a single-photon pulse through a scattering in an optical cavity. In this Letter, we investigate a scheme of atomic quantum memory to store photonic qubits in cavity QED. This is motivated on the recent observation that the quantum-state swapping between a single-photon pulse and a  $\Lambda$ -type atom trapped in a cavity is ideally realized via scattering for some specific case in the strong coupling cavity regime producing the maximal phase shift [14].

We consider a one-dimensional cavity bounded by two mirrors, one of which is perfectly reflecting while the other is partially transparent. The electromagnetic field is expanded in terms of the continuous modes with wave number  $k$ , which range over the inside of cavity through the outside free space [14]. A photonic qubit is encoded in the polarization states  $|k_L\rangle$  and  $|k_R\rangle$  of single-photon pulse as

$$|\phi_p\rangle = c_L|\bar{k}_L\rangle + c_R|\bar{k}_R\rangle, \quad (1)$$

$$|\bar{k}_{L,R}\rangle = \int_{-\infty}^{\infty} dk f(k) e^{-ikt} |k_{L,R}\rangle, \quad (2)$$

where  $f(k)$  is the normalized spectral amplitude, and  $e^{-ikt}$  represents the asymptotic temporal evolution ( $c = \hbar = 1$  unit). On the other hand, a  $\Lambda$ -type atom is trapped inside the cavity, which has two degenerate ground states  $|L\rangle$  and  $|R\rangle$  and an excited state  $|e\rangle$ . Then, an atomic

qubit is encoded in the degenerate ground states as

$$|\psi_a\rangle = a_L|L\rangle + a_R|R\rangle. \quad (3)$$

The polarization states  $|k_L\rangle$  and  $|k_R\rangle$  are coupled, respectively, to the transitions  $|L\rangle - |e\rangle$  and  $|R\rangle - |e\rangle$  of frequency  $\omega_e$  in the cavity with the dipole couplings

$$g_{L,R}(k) = \lambda_{L,R} \sqrt{\kappa/\pi} e^{i\theta_{L,R}} / (k - k_c + i\kappa), \quad (4)$$

where  $k_c$  is the resonant frequency of the cavity,  $\kappa$  is the leakage rate of the cavity,  $\lambda_L$  and  $\lambda_R$  represent the normalized coupling strengths, and  $\theta_L$  and  $\theta_R$  are the phase angles from the dipole transition matrix elements. The atom-photon scattering then takes place through these couplings, and the transformation of the atom-photon states is induced asymptotically as

$$\begin{aligned} \mathcal{T}|Lk_L\rangle &= T_{LL}(k)|Lk_L\rangle + T_{RL}(k)|Rk_R\rangle, \\ \mathcal{T}|Rk_R\rangle &= T_{LR}(k)|Lk_L\rangle + T_{RR}(k)|Rk_R\rangle, \\ \mathcal{T}|Lk_R\rangle &= |Lk_R\rangle, \quad \mathcal{T}|Rk_L\rangle = |Rk_L\rangle, \end{aligned} \quad (5)$$

where the basis states are taken as  $|Lk_L\rangle \equiv |L\rangle|k_L\rangle$ , and so on. The scattering matrix elements are calculated explicitly in Ref. [14] as

$$\begin{aligned} T_{LL}(k) &= e^{i\phi_s(k)} |\xi_L(k)|^2 + |\xi_R(k)|^2, \\ T_{RR}(k) &= e^{i\phi_s(k)} |\xi_R(k)|^2 + |\xi_L(k)|^2, \\ T_{LR}(k) &= \xi_L^*(k) \xi_R(k) (e^{i\phi_s(k)} - 1), \\ T_{RL}(k) &= e^{2i(\theta_L - \theta_R)} \xi_L^*(k) \xi_R(k) (e^{i\phi_s(k)} - 1), \end{aligned} \quad (6)$$

where  $\xi_{L,R}(k) \equiv g_{L,R}(k) / \sqrt{|g_L(k)|^2 + |g_R(k)|^2}$ . Here, the bright state acquires a phase shift  $\phi_s(k)$  via scattering. This linear transformation  $\mathcal{T}$  with a complex  $\phi_s(k)$  is generally non-unitary due to the loss with a rate  $\gamma$  induced by the spontaneous emission into the environment.

## Swapping for qubit memory

It is observed [14] that the quantum-state swapping between the atom and photon can be made ideally via

scattering in the specific case of the  $\Lambda$ -type atom with equal but opposite dipole matrix elements, i.e.,  $\lambda_L = \lambda_R = \lambda$  and  $e^{i(\theta_L - \theta_R)} = -1$ , which provides

$$g_L(k) = -g_R(k). \quad (7)$$

For example, we may take the D1 line of sodium with  $|L\rangle = |F=1, m_F=-1\rangle$ ,  $|R\rangle = |F=1, m_F=1\rangle$ ,  $|e\rangle = |F=1, m_F=0\rangle$ . In fact, with the maximal phase shift  $e^{i\phi_s(k_c)} = -1$  at the resonance for  $\kappa\gamma/\lambda^2 \rightarrow 0$ , we have the scattering matrix elements as

$$T_{LR}(k_c) = T_{RL}(k_c) = 1, \quad T_{LL}(k_c) = T_{RR}(k_c) = 0. \quad (8)$$

Then, the atom-photon swapping is obtained as

$$|\Phi_{\text{in}}^{(k)}\rangle = (a_L|L\rangle + a_R|R\rangle) \otimes (c_L|k_L\rangle + c_R|k_R\rangle), \quad (9)$$

$\Updownarrow$

$$|\Phi_{\text{swap}}^{(k)}\rangle = (c_R|L\rangle + c_L|R\rangle) \otimes (a_R|k_L\rangle + a_L|k_R\rangle). \quad (10)$$

We here note that this swapping is made in a reversible way via scattering. Hence it can be applied to implement an atomic quantum memory for the storage of unknown photonic qubits of polarization. The input photonic qubit is stored (*written*) via scattering, and it is retrieved (*read*) by injecting another single-photon pulse.

We now evaluate the fidelity of this atom-photon swapping for the specific case of  $g_L(k) = -g_R(k)$  providing  $T_{LR}(k) = T_{RL}(k)$  and  $T_{LL}(k) = T_{RR}(k) = 1 - T_{LR}(k)$ . Arbitrary atomic and photonic qubits in Eqs. (1), (3) and (9) may be taken as the initial state  $|\Phi_{\text{in}}\rangle$ . Then, the density operator of the output state via scattering is given by

$$\rho_{\text{out}} = |\Phi_{\text{out}}\rangle\langle\Phi_{\text{out}}| + (1 - \langle\Phi_{\text{out}}|\Phi_{\text{out}}\rangle)|0\rangle\langle 0|, \quad (11)$$

$$|\Phi_{\text{out}}\rangle = \mathcal{T}|\Phi_{\text{in}}\rangle = \int_{-\infty}^{\infty} dk f(k) e^{-ikt} |\Phi_{\text{out}}^{(k)}\rangle, \quad (12)$$

$$|\Phi_{\text{out}}^{(k)}\rangle = T_{LR}(k) |\Phi_{\text{swap}}^{(k)}\rangle + T_{LL}(k) |\Phi_{\text{in}}^{(k)}\rangle. \quad (13)$$

Here, the term of  $|0\rangle\langle 0|$  represents the loss due to the spontaneous emission with  $\text{Tr}\rho_{\text{out}} = 1$ . The output photon will eventually be absorbed by matter. Then, by taking the trace over the photon states the fidelity to obtain the desired atomic state  $|\psi_{\text{swap}}\rangle = c_R|L\rangle + c_L|R\rangle$  is given by

$$F = \left[ \langle\psi_{\text{swap}}| \text{Tr}_{(k)} \left[ |\Phi_{\text{out}}^{(k)}\rangle\langle\Phi_{\text{out}}^{(k)}| \right] |\psi_{\text{swap}}\rangle \right]_f, \quad (14)$$

where  $\text{Tr}_{(k)}[\rho] \equiv \langle k_L|\rho|k_L\rangle + \langle k_R|\rho|k_R\rangle$ , and the average of any function  $G(k)$  of  $k$  with the weight  $|f(k)|^2$  is denoted as

$$[G]_f \equiv \int_{-\infty}^{\infty} dk |f(k)|^2 G(k). \quad (15)$$

This fidelity is calculated by considering  $T_{LR}(k) + T_{LL}(k) = 1$  as

$$F(D) = F(0) + [1 - F(0)]D \quad (16)$$

with  $D = |\langle\psi_{\text{swap}}|\psi_a\rangle|^2 = |c_R^* a_L + c_L^* a_R|^2$  ( $0 \leq D \leq 1$ ). Hence, we may take the fidelity of swapping as

$$F_{\text{swap}} = F(0) = [T_{LR}(k)]_f^2 \quad (17)$$

irrespective to the choice of initial state. Here it is desired for optimizing the quantum-state transfer via swapping that the spectral width  $\kappa_p$  of the photon pulse with  $f(k)$  should be made sufficiently smaller than the cavity leakage rate  $\kappa$ , as discussed in Ref. [14]. Then, we have the quite high fidelity  $F_{\text{swap}} \simeq |T_{LR}(k_c)|^2 \simeq 1$  with  $\kappa_p \ll \kappa$  in the strong coupling regime  $\kappa\gamma/\lambda^2 \ll 1$ .

Numerically, by using the formula for the phase shift  $\phi_s(k)$  [14] we obtain  $F_{\text{swap}}(\text{Gaussian}) = 0.975$  typically with  $\lambda = 5\kappa$ ,  $\gamma = 0.5\kappa$  ( $\kappa\gamma/\lambda^2 = 0.02$ ) and  $\omega_e = k_c$  for the Gaussian  $|f(k)|^2 = \exp[-(k - k_c)^2/\kappa_p^2]/(\pi^{1/2}\kappa_p)$  with  $\kappa_p = 0.1\kappa$ . We also obtain  $F_{\text{swap}}(\text{Lorentzian}) = 0.887(0.960)$  with  $\lambda = 5\kappa$  and  $\gamma = 0.5\kappa$  for the Lorentzian  $|f(k)|^2 = (\kappa_p/\pi)[(k - k_c)^2 + \kappa_p^2]^{-1}$  with  $\kappa_p = 0.1\kappa(0.02\kappa)$ . The atomic detuning does not provide a significant effect on the fidelity for  $|\omega_e - k_c| \lesssim \gamma \sim \kappa$ .

#### Storage and retrieval with conditional measurements

We next consider the sequence of storage and retrieval of photonic qubit, which may appear somewhat different from simply repeating twice the atom-photon swapping. To be general, we relax the condition (7) for the  $\Lambda$ -type atom, allowing different  $g_L(k)$  and  $g_R(k)$ . In this situation, as seen below, even for a not so strong atom-photon coupling the almost faithful quantum memory operation can be achieved conditionally by making some projective measurements. Specifically, the initial state is taken as

$$|\Phi_{\text{in}}\rangle = |R\rangle|\phi_{p1}\rangle|\bar{k}'_R\rangle = |R\rangle(c_L|\bar{k}_L\rangle + c_R|\bar{k}_R\rangle)|\bar{k}'_R\rangle. \quad (18)$$

Here,  $|\phi_{p1}\rangle$  is the photonic qubit to be stored and then retrieved. The atomic state is initially prepared to be  $|R\rangle$ , and the second photon pulse of  $|\bar{k}'_R\rangle$  is injected after a time delay  $\tau (\gg \kappa_p^{-1} \gg \kappa^{-1})$  to retrieve the stored qubit. We take for definiteness the same profile  $f(k)$  for the two photon pulses, though this choice is not essential.

After the scattering of the first photon pulse with the atom, the detection of the polarization “L” is made on the output photon. This polarization detection is represented by a positive operator valued measure

$$\Pi(k_L) = \int_{-\infty}^{\infty} dk \eta(k) |k_L\rangle\langle k_L| \quad (19)$$

with the quantum efficiency  $0 < \eta(k) \leq 1$ . [The dark count is neglected here since it can actually be made rather small. The terms of more than one photon states may also be discarded effectively in  $\Pi(k_L)$  in the present process involving a single atom and photon.] Then, the resultant state is given by

$$\begin{aligned} \rho_1 &= P(k_L)^{-1} \text{Tr}_{p1} [\Pi(k_L) \mathcal{T}_1 |\Phi_{\text{in}}\rangle\langle\Phi_{\text{in}}| \mathcal{T}_1^\dagger] \\ &= P(k_L)^{-1} \int_{-\infty}^{\infty} dk \eta(k) |f(k)|^2 |\Phi_1^{(k)}\rangle\langle\Phi_1^{(k)}|, \end{aligned} \quad (20)$$

where

$$|\Phi_1^{(k)}\rangle = [T_{LR}(k)c_R|L\rangle + c_L|R\rangle]|\bar{k}'_R\rangle \quad (21)$$

by applying Eq. (5) for  $\mathcal{T}_1$ . It is noticed in Eq. (21) that the initial photonic qubit is transferred to the atomic qubit with slight modification by the factor  $T_{LR}(k)$ . The loss term of  $|0\rangle\langle 0|$  is projected out by the photon detection even with  $\eta(k) < 1$  (and the negligible dark count). The success probability of the photon detection is given by  $P(k_L) = [\eta(k)\langle\Phi_1^{(k)}|\Phi_1^{(k)}\rangle]_f$ , providing the normalization  $\text{Tr}_{\text{ap}2}\rho_1 = 1$ .

The retrieval of the photonic qubit is implemented by the scattering of the second photon pulse followed by the conditional detection of the atomic state  $|L\rangle$ . The resultant output state is given by

$$\begin{aligned} \rho_{\text{out}} &= P(L)^{-1}\langle L|\mathcal{T}_2\rho_1\mathcal{T}_2^\dagger|L\rangle \\ &= \frac{|T_{LR}(k_c)|^2}{P(k_L)P(L)} \\ &\quad \times \int_{-\infty}^{\infty} dk \eta(k) |f(k)|^2 |\phi_{\text{out}}^{(k)}\rangle \langle \phi_{\text{out}}^{(k)}|, \end{aligned} \quad (22)$$

where

$$\begin{aligned} |\phi_{\text{out}}^{(k)}\rangle &= \int_{-\infty}^{\infty} dk' f(k') e^{-ik'(t-\tau)} \\ &\quad \times [r_{LR}(k)c_R|k'_R\rangle + r_{LR}(k')c_L|k'_L\rangle] \end{aligned} \quad (23)$$

with

$$r_{LR}(k) \equiv T_{LR}(k)/T_{LR}(k_c). \quad (24)$$

It is found in Eq. (23) that with  $T_{LR}(k) \approx T_{LR}(k_c)$ , i.e.,  $r_{LR}(k) \approx 1$  in the vicinity of resonance  $|k - k_c| \lesssim \kappa_p \ll \kappa$  the output state is very closed to the desired photon state as retrieval:

$$|\phi_{\text{out}}^{(k)}\rangle \approx |\phi_{p2}\rangle = (c_L|\bar{k}'_L\rangle + c_R|\bar{k}'_R\rangle). \quad (25)$$

The net success probability of the storage and retrieval, providing the normalization  $\text{Tr}_{p2}\rho_{\text{out}} = 1$ , is given by

$$P(L)P(k_L) = |T_{LR}(k_c)|^2 \left[ \eta(k) \langle \phi_{\text{out}}^{(k)} | \phi_{\text{out}}^{(k)} \rangle \right]_f. \quad (26)$$

Then, by considering Eqs. (22)–(25) the fidelity for this operation of storage and retrieval is evaluated as

$$F(p1 \rightarrow a \rightarrow p2) = \frac{\left[ \eta(k) |\langle \phi_{p2} | \phi_{\text{out}}^{(k)} \rangle|^2 \right]_f}{\left[ \eta(k) \langle \phi_{\text{out}}^{(k)} | \phi_{\text{out}}^{(k)} \rangle \right]_f}. \quad (27)$$

As seen in Eq. (25), we can obtain the fidelity of almost unity with  $r_{LR}(k) \approx 1$  for  $|k - k_c| \lesssim \kappa_p \ll \kappa$ , even if the atom-photon coupling is not so strong as  $\lambda_{L,R} \sim \kappa \sim \gamma$  to give  $|T_{LR}(k_c)|^2 \sim 0.1$ . Specifically, by considering that the quantum efficiency may be constant as  $\eta(k) = \eta$  in the vicinity of resonance, the fidelity is calculated as

$F(p1 \rightarrow a \rightarrow p2) = F_{\text{qm}} + [1 - F_{\text{qm}}]|c_L|^4$  depending on the initial  $|\phi_{p1}\rangle$ . Then, the fidelity of this quantum memory operation is given by

$$F_{\text{qm}} = |[r_{LR}]_f|^2 / |[r_{LR}]^2|_f \simeq 1 \quad (\kappa_p \ll \kappa). \quad (28)$$

This is a quite remarkable feature of the present conditional scheme for quantum memory, without requiring the specific  $\Lambda$ -type atom satisfying the condition (7) on the dipole couplings. Although some modification is made on the stored atomic state, as seen in Eq. (21), it is nearly compensated by the read-out process, as seen in Eq. (23), realizing the almost faithful retrieval of the initial photonic qubit. The trade-off of the success probability is instead paid to obtain the high fidelity for the general case.

Numerically, we have estimates of the fidelity and the net success probability as  $F_{\text{qm}} = 0.995, 0.994, 0.999$ , and  $P(L)P(k_L) = (0.975, 0.634, 0.248)\eta$ , for  $\lambda_L = \lambda_R = (5, 1, 0.5)\kappa$ , respectively with  $\gamma = 0.5\kappa$ ,  $\omega_e = k_c$  and  $\kappa_p = 0.1\kappa$  for the Gaussian form. Similar estimates are also obtained for the Lorentzian form with  $\kappa_p = 0.01\kappa$ . Therefore, the quite high fidelity  $F_{\text{qm}}$  is really obtained almost independently of the atom-photon coupling  $\lambda_{L,R}/\kappa \gtrsim 0.5$ .

It should be mentioned that the atomic detection of  $|L\rangle$  can be implemented by injecting the third photon pulse. Specifically, by injecting the photon of  $|\bar{k}'_L\rangle$  followed by the polarization detection  $\Pi(k''_R)$  on the output photon, the  $|L\rangle$  component of the initial atomic state is transformed to  $|R\rangle$  via scattering with the success probability  $\approx \eta|T_{RL}(k_c)|^2$  while the  $|R\rangle$  one is projected out.

In a feasible experiment, a sufficiently weak coherent light of  $|\alpha\rangle$  may be used as an actual single-photon source, though the success probability becomes rather small proportional to  $|\alpha|^2$ . The vacuum contribution is projected out conditionally by the detection of the output photon. The contributions of more than one photon states are small enough for  $|\alpha|^2 \ll 1$ .

### Storage of 2-qubit entanglement

We can see that the quantum-state transfer via scattering can also be applied to the storage of 2-qubit entanglement. We prepare two atomic memories and a polarization-entangled pair of photon pulses. Each photon pulse is scattered with the atom inside the respective cavity. In this situation, particularly for the ideal case of  $T_{LR} = T_{RL} = 1$  and  $T_{LL} = T_{RR} = 0$ , we obtain the swapping between the generic states of atom pair and photon pair, which may be either entangled or separable, as

$$\begin{pmatrix} a_{LL} \\ a_{RR} \\ a_{LR} \\ a_{RL} \end{pmatrix}_a \otimes \begin{pmatrix} c_{LL} \\ c_{RR} \\ c_{LR} \\ c_{RL} \end{pmatrix}_p \Leftrightarrow \begin{pmatrix} c_{RR} \\ c_{LL} \\ c_{RL} \\ c_{LR} \end{pmatrix}_a \otimes \begin{pmatrix} a_{RR} \\ a_{LL} \\ a_{RL} \\ a_{LR} \end{pmatrix}_p, \quad (29)$$

where the basis states are taken as for the atom pair “a” ( $|LL\rangle, |RR\rangle, |LR\rangle, |RL\rangle$ ) and for the photon pair “p” ( $|k_L k_L\rangle, |k_R k_R\rangle, |k_L k_R\rangle, |k_R k_L\rangle$ ).

This sort of 2-qubit transfer can readily be applied to the storage of photonic polarization entanglement as

$$c_{LR}|\bar{k}_L\rangle|\bar{k}'_R\rangle + c_{RL}|\bar{k}_R\rangle|\bar{k}'_L\rangle \Rightarrow c_{RL}|LR\rangle + c_{LR}|RL\rangle. \quad (30)$$

Specifically, by taking the initial state

$$|\Phi_{\text{in}}\rangle = |RR\rangle(c_{LR}|\bar{k}_L\rangle|\bar{k}'_R\rangle + c_{RL}|\bar{k}_R\rangle|\bar{k}'_L\rangle), \quad (31)$$

we obtain the  $(kk')$ -component of the output state via scatterings in the cavities 1 and 2 as

$$|\Phi_{\text{out}}^{(kk')}\rangle = [T_{LR}(k)c_{RL}|LR\rangle + T_{LR}(k')c_{LR}|RL\rangle]|k_L k'_L\rangle + |RR\rangle|\tilde{\phi}_{LR}^{(kk')}\rangle, \quad (32)$$

where  $|\tilde{\phi}_{LR}^{(kk')}\rangle = T_{RR}(k')c_{LR}|k_L k'_R\rangle + T_{RR}(k)c_{RL}|k_R k'_L\rangle$ . Then, the fidelity for the unconditional operation of entanglement transfer is evaluated by tracing over the photon states and the environment denoted by  $|0\rangle\langle 0|$ . For any choice of the initial state it is calculated to be bounded as  $F(p \rightarrow a) \geq |[T_{LR}]_f|^2 = F_{\text{swap}}F_{\text{qm}}$ , which approaches unity for the specific case of  $g_L(k) = \pm g_R(k)$  with  $e^{i\phi_s(k_c)} = -1$  in the strong coupling limit. Furthermore, we can make actively the photon detection  $\Pi(k_L) \otimes \Pi(k'_L)$  on the output state in Eq. (32), so that the trade-off of the success probability is made to obtain the high fidelity. Then, the transfer of the photonic entanglement to the atomic memories is implemented almost faithfully even for  $\lambda_{L,R} \sim \kappa \sim \gamma$ , and the fidelity is calculated to be the same as the 1-qubit memory,

$$F_{\text{ent-tr}} = F_{\text{qm}} \simeq 1 \quad (\kappa_p \ll \kappa). \quad (33)$$

The entanglement stored in the pair of atomic quantum memories is alternatively retrieved by injecting single-photon pulses (may be separable) to the atomic memories. In a feasible experiment for this entanglement transfer, a type II down-conversion light can be used as the input polarization-entangled photonic qubit.

In summary, we have investigated a scheme of atomic quantum memory to store photonic qubits in cavity QED. Specifically for a  $\Lambda$ -type atom with equal but opposite dipole matrix elements, which is trapped inside an optical cavity, the quantum-state swapping between a single-photon pulse and the atom is ideally realized via scattering in the strong coupling cavity regime. We have derived a simple formula for calculating the fidelity of this atom-photon swapping for quantum memory. We have further proposed a feasible method to implement conditionally the quantum memory operation with the fidelity of almost unity even for not so strong atom-photon couplings, which is applicable for a general  $\Lambda$ -type atom with degenerate ground states. This method can also be applied to store an photonic entanglement in spatially separated atomic quantum memories.

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